Effects of Hurricanes on Ambient Noise in the Gulf of Mexico

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Abstract - **Long-term omni-directional ambient noise was collected at several sites in the Gulf of Mexico during 2004 and 2005. The Naval Oceanographic Office deployed bottom-moored Environmental Acoustic Recording System (EARS) buoys approximately 159 nautical miles south of Panama City, Florida, in water depths of 3200 meters. The hydrophone of each buoy was 265 meters above the bottom. The buoys were located near a major shipping lane, with an estimated 1.5 to 4.5 ships per day passing nearby. The data duration was 14 months, and data were sampled at 2500 Hz with a bandwidth of 10-1000 Hz.**

Data were processed in eight 1/3-octave frequency bands, centered from 25 to 950 Hz. Monthly values of the following statistical quantities were computed from the resulting eight time series of noise spectral level: mean, median, standard deviation, skewness, kurtosis, and coherence time (the time for the autocorrelation function of each time series to fall to e^{-1} of its central, zero-lag value).

Four hurricanes were recorded during the summer of 2004, and they had a major impact on all of the noise statistics. Hurricane Charlie was recorded in August, followed by Hurricanes Frances, Ivan, and Jeanne in September. Nearby National Data Buoy Center (NDBC) weather buoys recorded wind speed and wave height data, which allowed for comparison of underwater noise levels with the wind speed and significant wave height data during extreme weather conditions.

During hurricane conditions, the ambient noise levels at higher frequencies (400-950 Hz) are elevated, as expected, and are highly correlated with the wind and wave height data. The ambient noise levels at lower frequencies (25-100 Hz) are depressed, perhaps an indicator of less shipping activity during extreme wind conditions. The fewest number of peaks, as well as troughs, per day in the noise levels are observed from 200-950 Hz, yielding the smallest estimate of nearby ships per day. The average time between peaks, as well as troughs, is maximum from 200-950 Hz.

The variability of the data is high at higher frequencies (400-950 Hz) during hurricanes, as indicated by the standard deviation and the spread of the data (the difference between the 10^{th} and the 90^{th} percentiles). The skewness is positive from 25-400 Hz and negative from 630-950 Hz. The kurtosis is high from 50-100 Hz, peaking at 100 Hz. The coherence time peaks during hurricanes in the higher frequency bands. The coherence time is maximum from 200-950 Hz, ranging from 10 hours at 200 Hz to 33 hours at 950 Hz.

The passage of Hurricane Ivan is analyzed in detail. Ivan was actually recorded twice. Ivan passed by the EARS buoys once, went ashore near the Alabama-Florida border, moved into the Atlantic Ocean, and then its remnants came back into the Gulf of Mexico a second time. During its first approach, Ivan was a Category 4 hurricane as its eye passed within 101 nmi of the EARS buoys. Its acoustic effects were evident for a 3-day period. Noise levels in higher frequency bands increased by approximately 11 dB per day during Ivan's first approach and decreased by approximately 11 dB per day as Ivan departed the EARS buoy's range.

I. Introduction

The Naval Oceanographic Office has been deploying Environmental Acoustic Recording System (EARS) buoys to record long-term ambient noise in the ocean since 1996. In 2004 and 2005 seven EARS buoys of a new design were deployed in the Gulf of Mexico. These bottom-mounted, omni-directional buoys were deployed in a region with water depths of around 3200 meters; the hydrophone depths were around 2935 meters (the hydrophones were moored about 265 meters above the bottom). The recovered data are of high quality and consist of almost 14 months of continuous recording at a sampling rate of 2500 Hz. The data have a useful bandwidth of 10-1000 Hz.

Data were processed in eight 1/3-octave frequency bands, centered from 25 to 950 Hz. For each of the 14 months recorded, values of the following statistical quantities were computed from the resulting eight time series of noise spectral level: mean, median, standard deviation, skewness, kurtosis, coherence time, and the 10^{th} and 90^{th} percentiles [1].

II. Methodology

This paper will focus on the data from one of the buoys, labeled EARS A1. This buoy was deployed in April 2004 and recovered in May 2005. At site A1, raw data were sampled continuously for 14 months at 2500 Hz. Time periods corrupted by clipping and spinning of the hard disks inside the EARS buoy were removed during processing (Fig. 1). The remaining data were processed using the Bartlett method with a Hann window [2] and a 2048-point non-overlapping Fast Fourier Transform (FFT), corresponding to 0.82 seconds of data.[1] This process was repeated 732 times for each 10-minute segment of raw data (732 x 0.82 seconds = 10 minutes). The 732 resulting periodograms were then averaged using a 90% acceptance factor. At least 659 out of

[1] A 0.82-second segment of data was read in and multiplied by a Hann window in the time domain. A 2048-point FFT was computed for this segment, and the periodogram estimate was calculated.

the 732 segments of data had to contain valid data for the 10-minute average periodogram to be accepted. Using this criterion, every 10-minute period for the entire 14 months was accepted. Each 10-minute average result was converted to decibels (dB). (All noise levels in this paper are computed as spectrum levels, with units of dB reference 1 micropascal squared per Hz.) This yielded the Power Spectral Density (PSD) estimate for this 10-minute segment of data. This process was repeated for the next 10-minute segment of data (with no overlap) until the entire 14-month data set was processed. At this point the processed data have a frequency resolution given by Δf = 2500Hz / 2048 = 1.22 Hz.

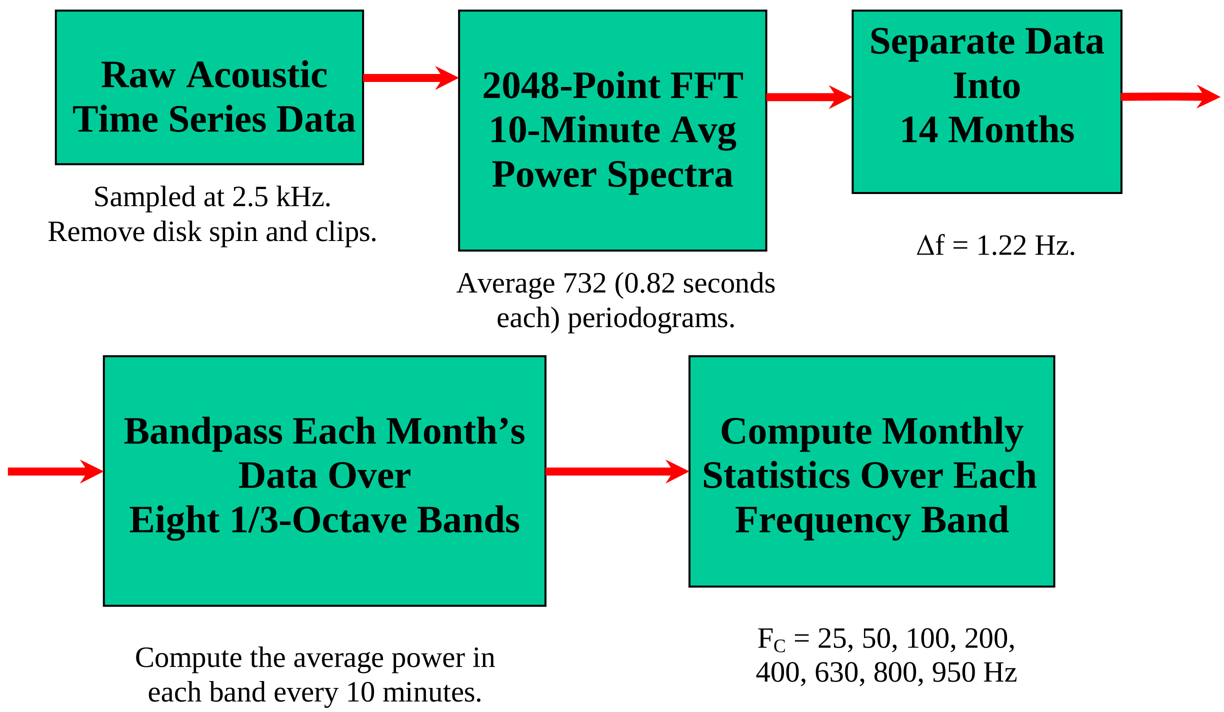

Fig. 1 Data processing.

The data were then separated into 14 monthly intervals, and each month's data were separated into eight 1/3-octave frequency bands. Table I shows the third-octave bandwidths for each center frequency, F_c. The first seven values, from 25-800 Hz, are standard 1/3-octave center frequencies. The last value, 950 Hz, was chosen as the approximate geometric mean frequency of the band 900-1000 Hz. The raw data from 1000-1250 Hz were potentially aliased and therefore were not used in this analysis.

TABLE I
THIRD-OCTAVE CENTER FREQUENCIES AND BANDWIDTHS

Center Frequency F_c (Hz)	**1/3-Octave Bandwidth (Hz)**
25	22-28
50	45-56
100	90-112
200	180-224
400	355-450
630	560-710
800	710-900
950	900-1000

The 1/3-octave bands were processed using the Daniell method [2]. The PSD estimate for a 10-minute segment of data (with a frequency resolution of 1.22 Hz) was retrieved, and the dB values at each frequency were converted back to power units (μPa^2). The power values were averaged in the frequency domain within the appropriate 1/3-octave band limits (Table I). After the average power in μPa^2 for each 1/3-octave band was determined, the result was converted back to dB. At this point in the processing, one number represents the average power (in dB re 1 μPa^2 per Hz) in each 1/3-octave band for this 10-minute segment of data. This process was repeated for all 10-minute segments in a month. The monthly statistics were then computed for each 1/3-octave band. A 30-day month contains approximately 4320 data points for each 1/3-octave band.

III. Environmental Information

The National Oceanic and Atmospheric Administration (NOAA), through the National Data Buoy Center (NDBC), operates a network of weather buoys in the Gulf of Mexico [3]. Two NDBC buoys close to the EARS buoys recorded wind speed and wave height data for the entire period the EARS buoys were recording. Station 42003 is located 260 nmi south of Panama City, Florida, at a water depth of 3233 m (Fig. 2). The water depth at station 42003 is 3200 m, very close to the water depth in the vicinity of the EARS buoys. Station 42003 is located 89 nmi south/southeast of EARS A1; the EARS buoys location and station 42003 are both in the Mexican Basin physiographic region in the eastern Gulf of Mexico, near the West Florida Escarpment. Station 42036 is located 106 nmi west/northwest of Tampa, Florida, on the West Florida Shelf, at a water depth of 55 m. It is located 103 nmi northeast of the EARS A1 location. The two NDBC buoys are 164 nmi apart [1].

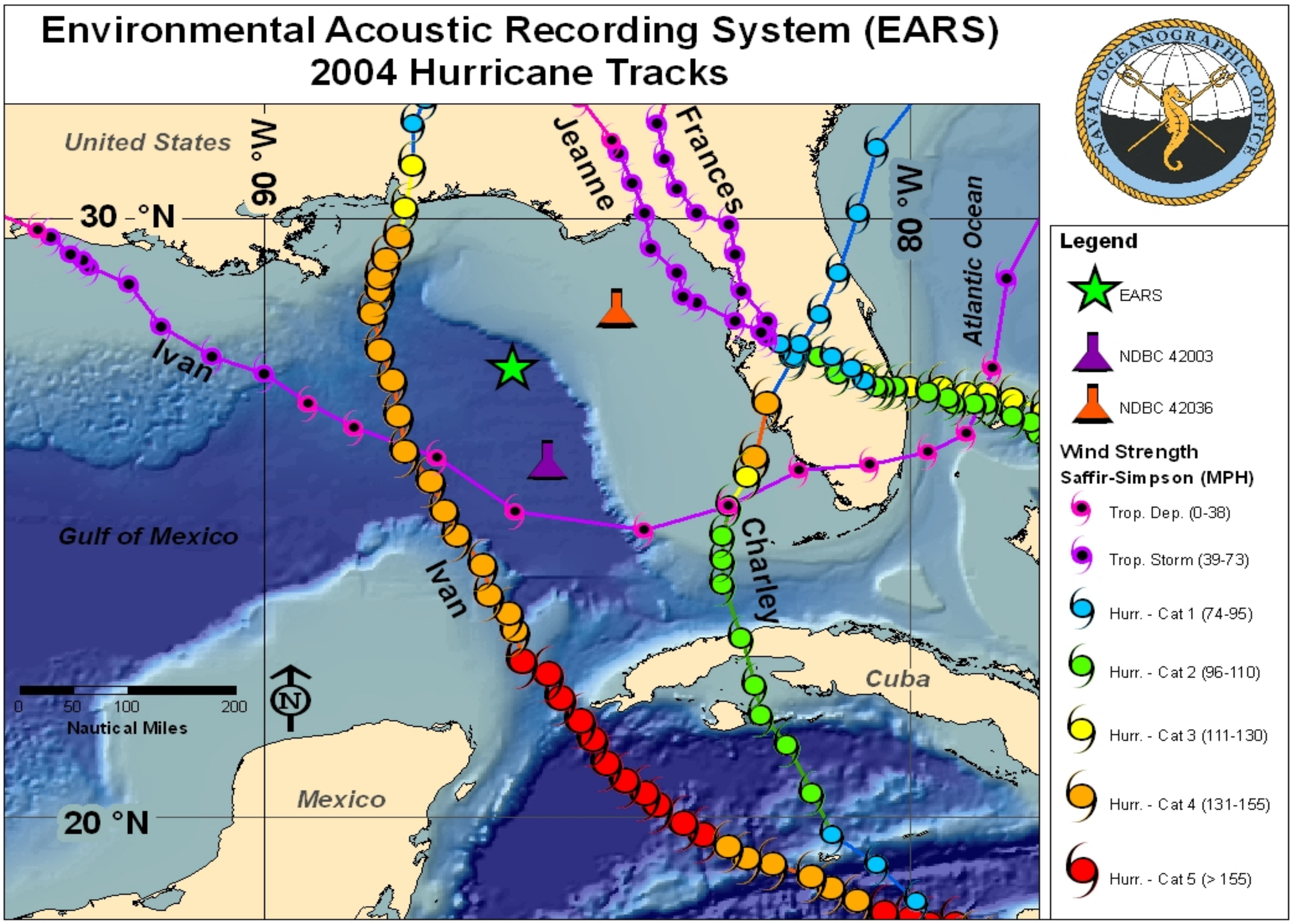

Fig. 2 Location of EARS buoy, NDBC weather buoys, and summer 2004 hurricane tracks.

IV. Ambient Noise Results

The monthly mean ambient noise values peak at 25 and 50 Hz, then decrease with increasing frequency out to 950 Hz (Fig. 3). Most frequency bands appear to have a cycle of about one year, based on the monthly mean values. The low frequencies (25-100 Hz) peak during March 2005 and are minimum during the hurricane month of September 2004. High frequencies (400-950 Hz) are loudest during September 2004 and during the winter months of November, December, and January due to high average wind speeds during these months. Conversely, the high frequencies are quietest during the summer months of June through August of 2004 due to low average wind speeds during these months.

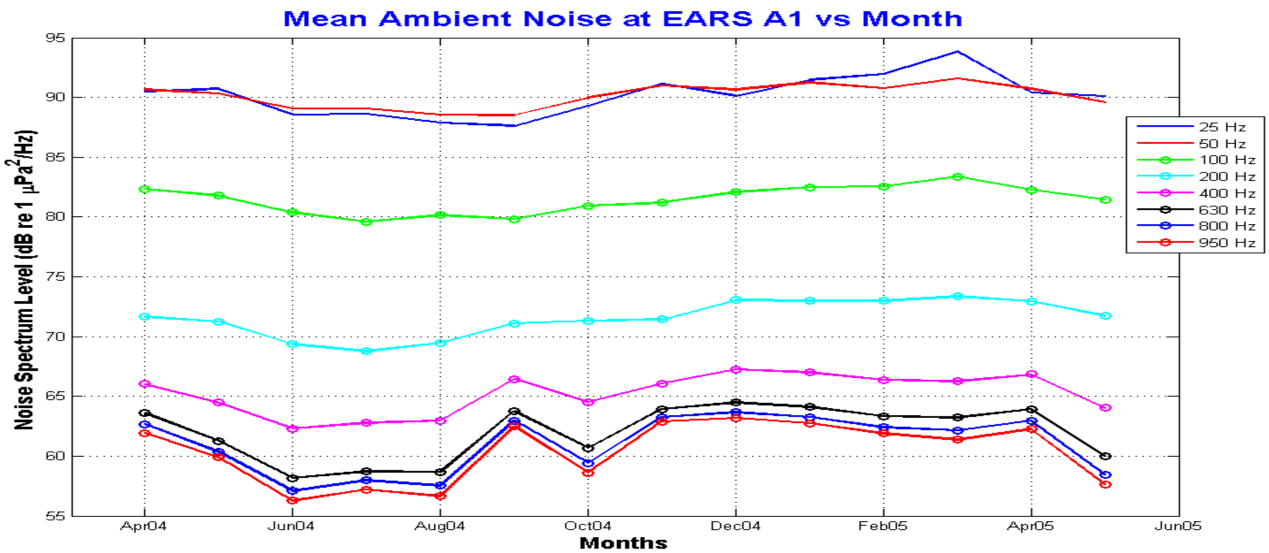

Fig. 3 Mean ambient noise vs. month.

The standard deviation (Fig. 4) tends to be high at low frequencies (25 Hz), is smallest near 100-200 Hz, and increases to high values again at high frequencies (630-950 Hz). The highest standard deviations occur during September 2004 from 630-950 Hz due to the high wind speed variability during the hurricanes. The same pattern, although not as pronounced, was observed during May 2005.

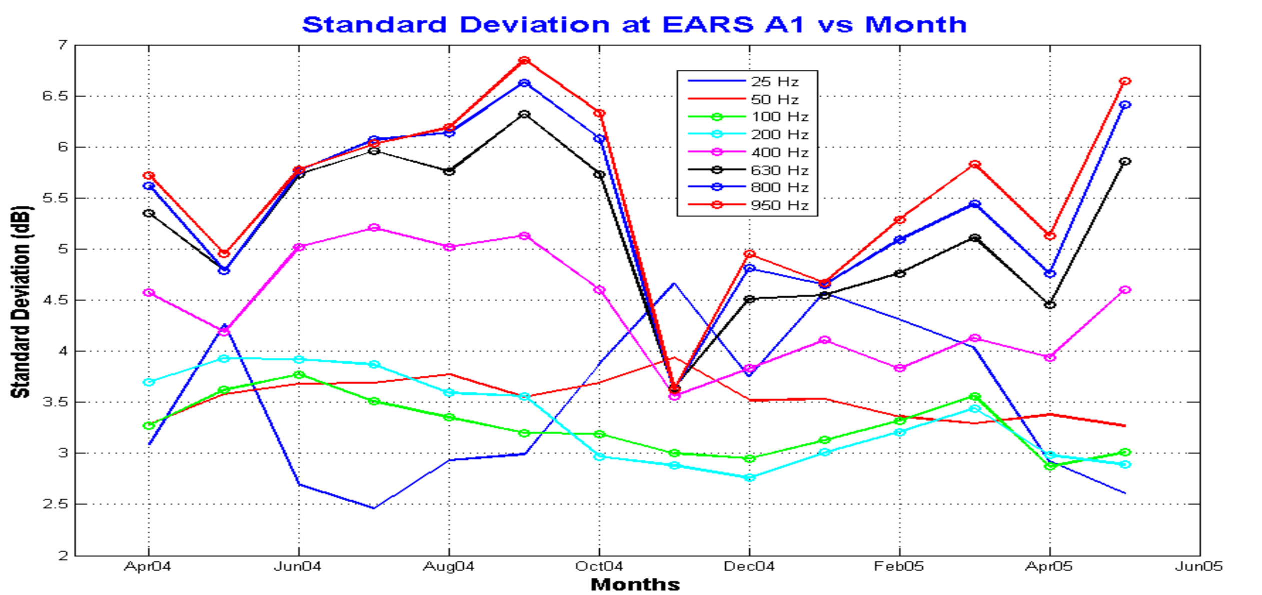

Fig. 4 Standard deviation vs. month.

The skewness (Fig. 5) tends to be low at low frequency (25 Hz), increasing to a maximum at 100 Hz, and then decreasing again at higher frequencies, with the lowest values at 950 Hz. The skewness is always positive (skewed towards peaks) from 25-400 Hz, except at 25 Hz during January-March 2005. Since shipping noise dominates low frequencies [4], the region 25-400 Hz is dominated by shipping peaks, which contribute to the high amplitude tails (louder decibel values) of a probability density function (PDF) and make the skewness positive.

Weather noise dominates high frequencies [4], so we expect the region 630-950 Hz to be dominated by weather. The average weather in a month determines the skewness in that month at higher frequencies [1]. The skewness is usually negative (skewed towards troughs) from 630-950 Hz, especially in months with high average wind speeds. Of the 14 months analyzed, 11 months had average wind speeds of 9 knots or greater, and these months are generally negatively skewed in the region of 630-950 Hz. The skewness is positive from 630-950 Hz when the monthly average wind speed is low, such as occurred during June to August 2004, when the monthly average wind speed ranged from 7.3 to 7.8 knots. In general, the skewness is positive when the mean is greater than the median and negative when the median is greater than the mean. The most negative values of skewness at 630-950 Hz occur during February 2005, a very windy month with an average wind speed of 12.1 knots [1].

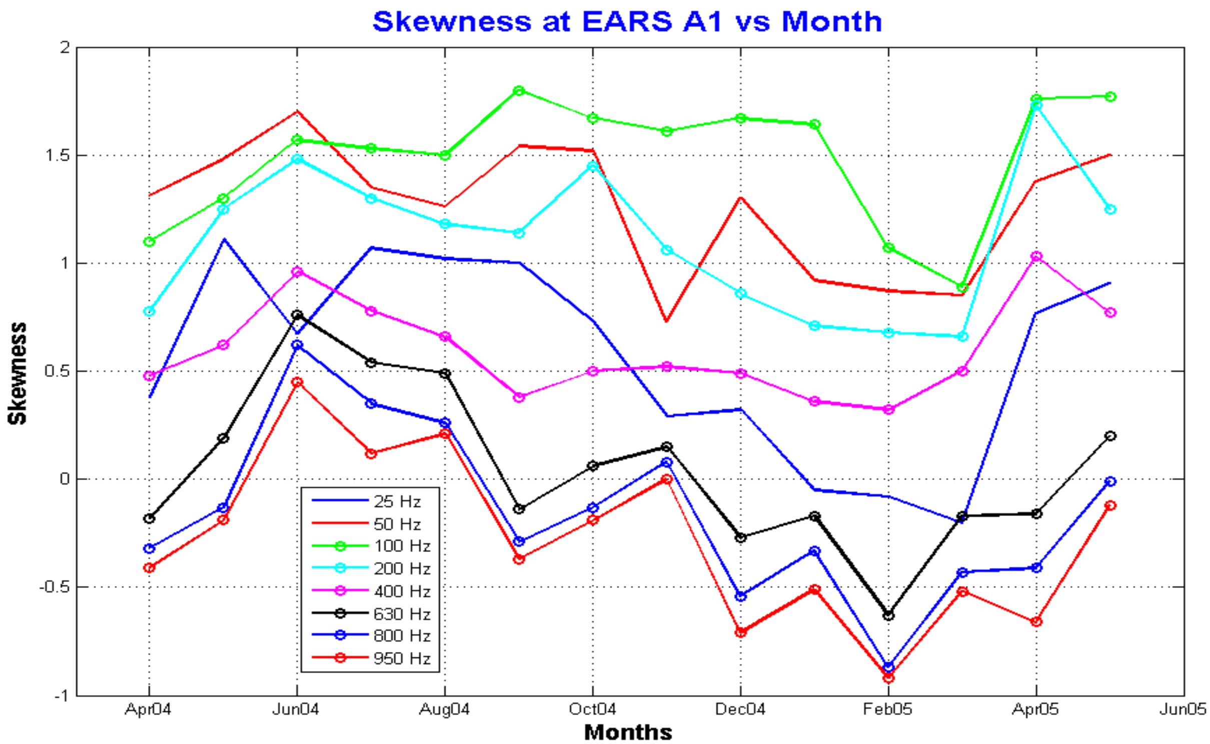

Fig. 5 Skewness vs. month.

The temporal coherence of the noise field was analyzed by computing the autocorrelation function for each of the eight 1/3-octave band time series for each month. The time for the autocorrelation to fall to e^{-1} of its central (zero-lag) value is called the coherence time.[2] The coherence time is a measure of the effective width of the autocorrelation function, or how long a time series is coherent with itself. The coherence times (Fig. 6) range from a low value of about 1 hour to a high value of about 33 hours. The coherence time is generally low at low frequencies in the shipping band (25-400 Hz) year-round, and at higher frequencies in the weather band (630-950 Hz) when the average monthly wind speed is low (such as June through August of 2004). It is generally high at higher frequencies (630-950 Hz) when the average monthly wind speed is high. The highest values are observed during the hurricane month of September 2004 at all frequencies above 200 Hz, with the maximum being 32.66 hours at 950 Hz.

The monthly time series for each of the frequency bands was also analyzed for peaks and troughs. This was done in order to determine how often and for how long it was noisy or quiet as a function of frequency and month. The following quantities were computed for the peaks and troughs: peaks and troughs per day, peak and trough duration (time above and below a specified threshold), and peak or trough inter-arrival time (the interval between peaks or troughs). Two types of thresholds were investigated. One was an absolute threshold for each frequency band and month: the 10th percentile for troughs and the 90th percentile for peaks. The second was a relative threshold, based on a 6-hour running average of the data and the monthly standard deviation in each frequency band.

[2] Some authors call this the *correlation time* or the *decorrelation time*.

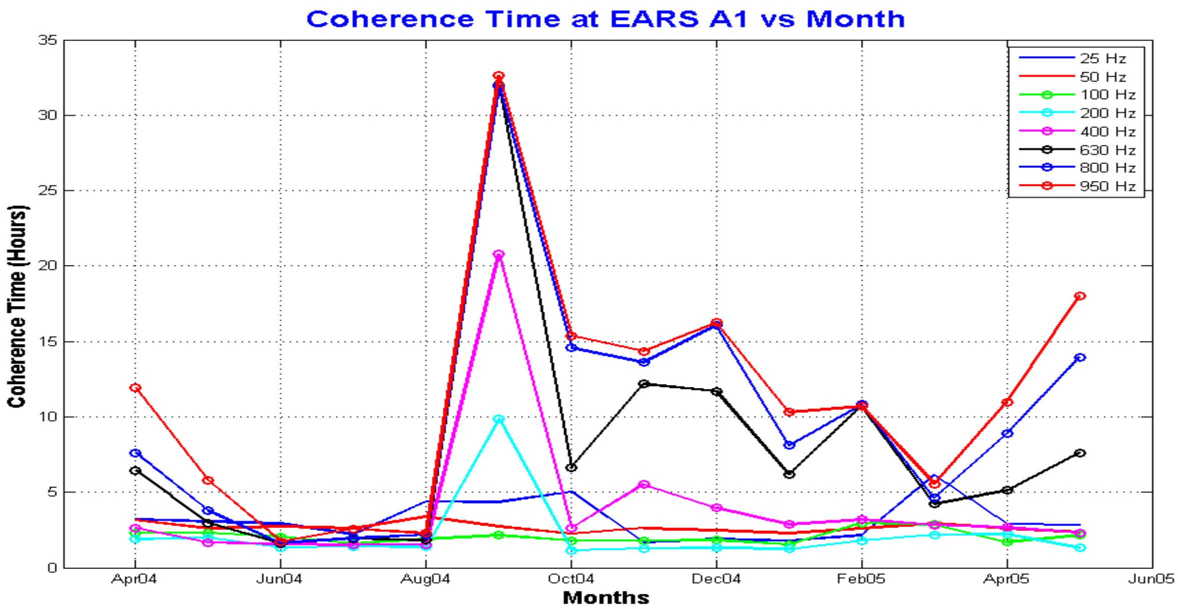

Fig. 6 Coherence time vs. month.

The number of peaks in a month was computed by counting the number of times the data in a time series exceeded the 90th percentile during the month. The duration of each peak was computed by subtracting each up-threshold-crossing time from its corresponding down-threshold-crossing time. The average number of peaks per day was computed by dividing the total number of peaks in a month by the number of days in that month. The average peak duration for a month was computed by adding the durations of each peak for that month and dividing by the total number of peaks.

The inter-arrival times (IAT) between peaks were computed by subtracting the up-threshold-crossing time of each peak from the up-threshold-crossing time of the peak immediately following the peak being analyzed. The average IAT for peaks during a month was computed by adding the IATs for each pair of peaks during the month and dividing by the total number of intervals.

Similarly, the number of troughs in a month was computed by counting the number of times the data in a time series fell below the 10th percentile during the month. The duration of each trough and the IAT between troughs were computed in a similar fashion to the duration and IAT of the peaks.

The absolute threshold method, based on the 10th and 90th percentiles, works well for stationary data; however, during the course of a month, the data are not stationary. The mean values in different frequency bands fluctuate in response to storms, hurricanes, and changing shipping patterns.

The non-stationarity of the data over the course of a month was addressed by using a relative threshold method. For each frequency band and month, a 6-hour running average of the time series was computed. The actual time series, with a data point every 10 minutes, was then compared to the local mean value of the data, based on looking 3 hours forward and 3 hours backward. If the time series exceeded a threshold above the 6-hour mean, that period was counted as a peak. Similarly, if the time series went lower than a threshold below the 6-hour mean, that period was counted as a trough. The threshold was based on the standard deviation (σ) computed for the month and frequency band under consideration. The threshold was set at 0.6745σ for peaks and at -0.6745σ for troughs.[3]

In higher frequency bands, the noise due to weather dominates and determines the average ambient noise background level at a given time. However, a ship passing close to a hydrophone can easily surpass this background noise level. Ship passages can easily be seen on a spectrogram [1]. Thus, the peaks in higher frequency bands are usually an indicator of nearby ships.[4]

The hurricane month of September 2004 presents a good example of how high frequency acoustic data are highly correlated with the weather. Fig. 7 shows the spectrogram for September 2004. Three hurricanes were recorded by the EARS buoys that

[3] The numerical factor 0.6745 was determined from the 25th and 75th percentiles for a Gaussian distribution. Twenty-five percent of the data in a Gaussian distribution exceed the mean value plus 0.6745σ; 25% of the data fall below the mean value minus 0.6745σ [5].

[4] Peaks in higher frequency bands may also be caused by intense rain and wind activity during extreme weather events [6].

month: Frances, Ivan,[5] and Jeanne. Fig. 8 shows a comparison of the acoustic data in the 900-1000 Hz band and the wind speed data recorded at NDBC buoy 42003. To make the comparison, the EARS data were averaged over one hour to match the averaging interval of the wind speed data, and then both data sets were normalized (zero mean, unity variance).[6] The correlation is excellent. There is an obvious time lag near day 14 because Ivan passed by the weather buoy before it passed by the EARS buoy. Even with this time lag, the correlation coefficient for these two time series is 0.77.

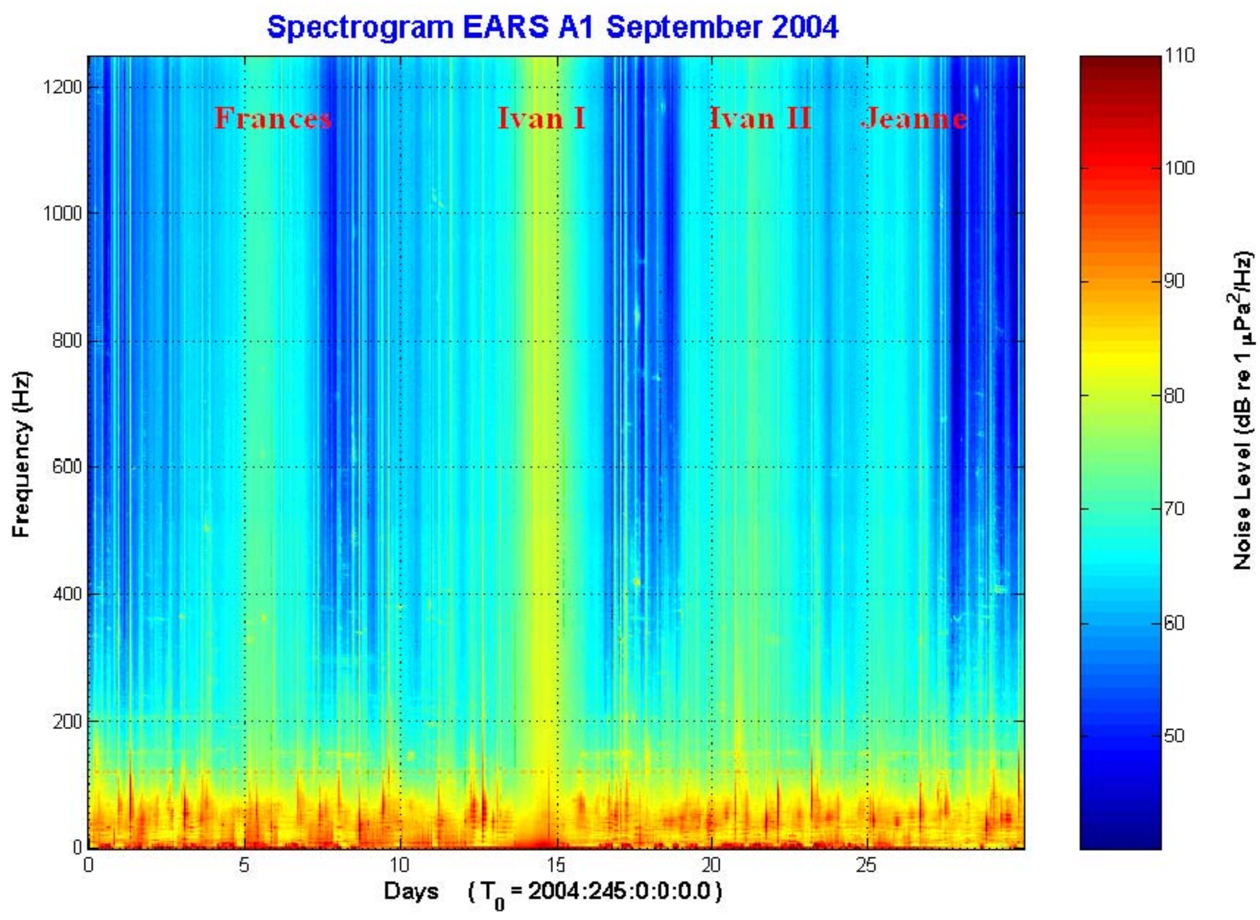

Fig. 7 Spectrogram for September 2004.

Fig. 9 shows the average number of peaks per day using both methods (absolute and relative thresholds) for the two highest frequency bands analyzed, 800 and 950 Hz. Both methods show a high value during August 2004, although the relative threshold shows a higher value (about 4.2 peaks/day at 950 Hz versus about 3.2 peaks/day for the absolute threshold). Both methods show a sharp drop in peaks/day during September 2004. As stated previously, the peaks in higher frequency bands are usually an indicator of nearby ships. Even though the acoustic data from August 2004 included the noise from Hurricane Charlie, this was a relatively mild month in terms of weather, with an average wind speed of 7.8 knots. It makes sense that a relatively high number of ships would pass in close proximity to the EARS buoys during good weather. However, September 2004 was a stormy month, with three hurricanes pushing the average wind speed to 15.0 knots, resulting in less ship traffic.

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[5] Ivan was actually recorded twice. Ivan passed by the EARS buoys once, went ashore near the Alabama-Florida border, moved into the Atlantic Ocean, and then its remnants came back into the Gulf of Mexico a second time (Fig. 2).

[6] For each data set, the data were put in standard normalized form: the mean value was subtracted from each data point, and then the result was divided by the standard deviation.

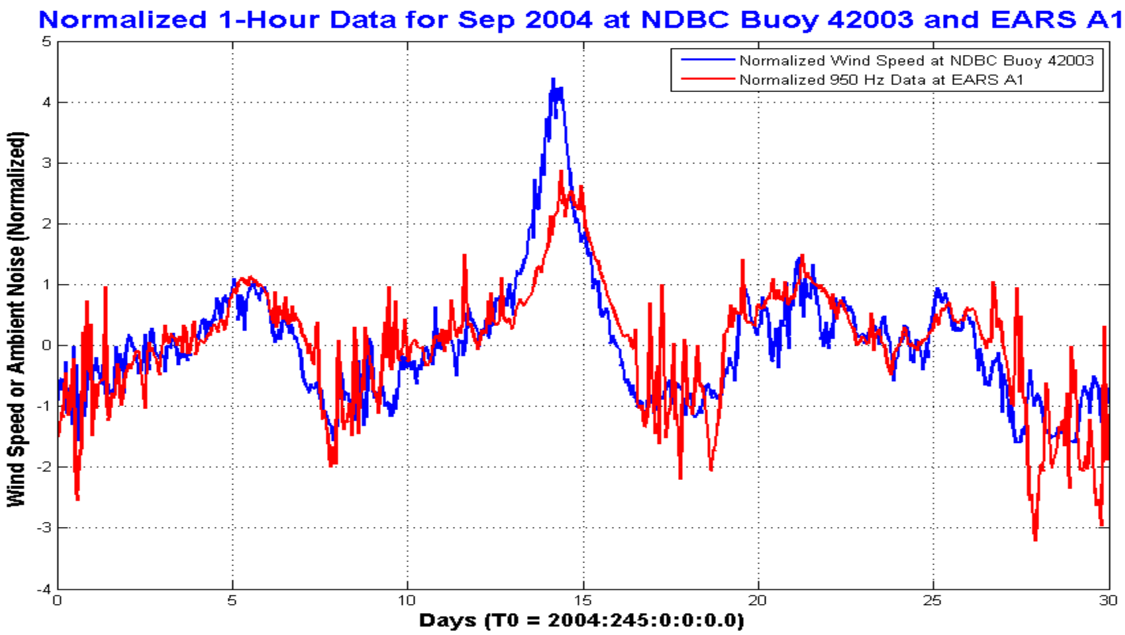

Fig. 8 September 2004 wind speed and acoustic data (950-Hz) comparison.

The shipping estimate increased in October, after the hurricane season had passed the busier summer months. During some months both absolute and relative methods gave similar estimates for nearby shipping activity, but in general the relative method yielded slightly higher estimates. Fig. 9 illustrates the estimated number of ships passing the EARS buoy each day ranges from a low value of about 1.5 (September 2004) to a high value of about 4.5 (August 2004).

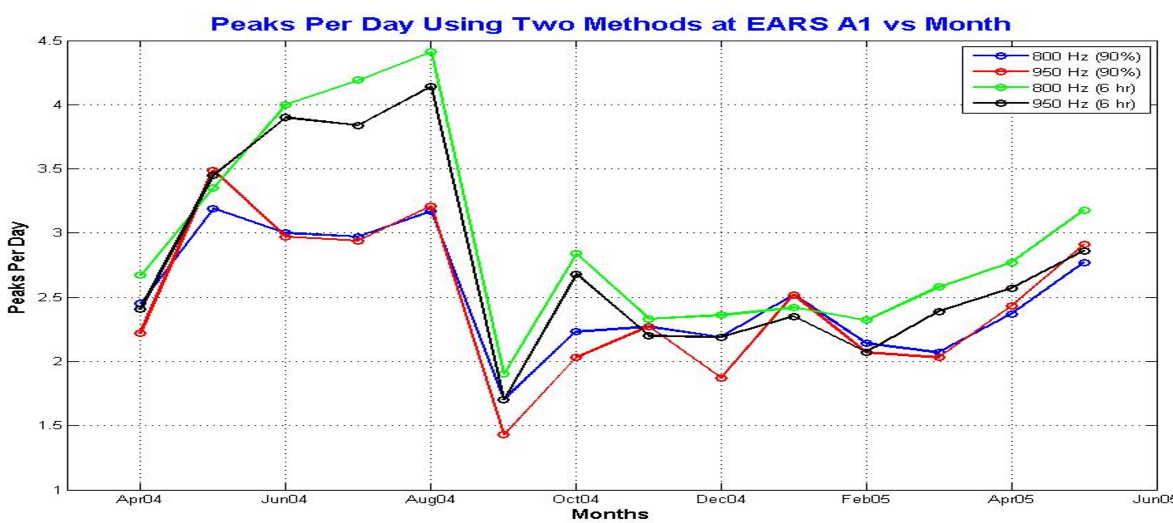

Fig. 9 Peaks per day vs. month using both methods.

IV. Ambient Noise During Hurricane Ivan

Hurricane Ivan actually passed by the EARS buoys twice (Fig. 2). During its first approach, Ivan was a Category 4 hurricane as its eye passed within 101 nmi of the EARS buoys. Its acoustic effects were evident for a 3-day period (Fig. 10). Fig. 10 shows the ambient noise recorded by EARS A1 during the first passage of Hurricane Ivan in three 1/3-octave bands centered at 200, 400, and 800 Hz. A 6-hour running average (acting as a low-pass filter) was applied to the 10-minute ambient noise data. On average, noise levels were raised about 12 dB above background during Ivan's passage in each of the frequency bands. Noise levels in each of these frequency bands increased by approximately 11 dB per day during Ivan's first approach and decreased by approximately 11 dB per day as Ivan departed the EARS buoy's range.

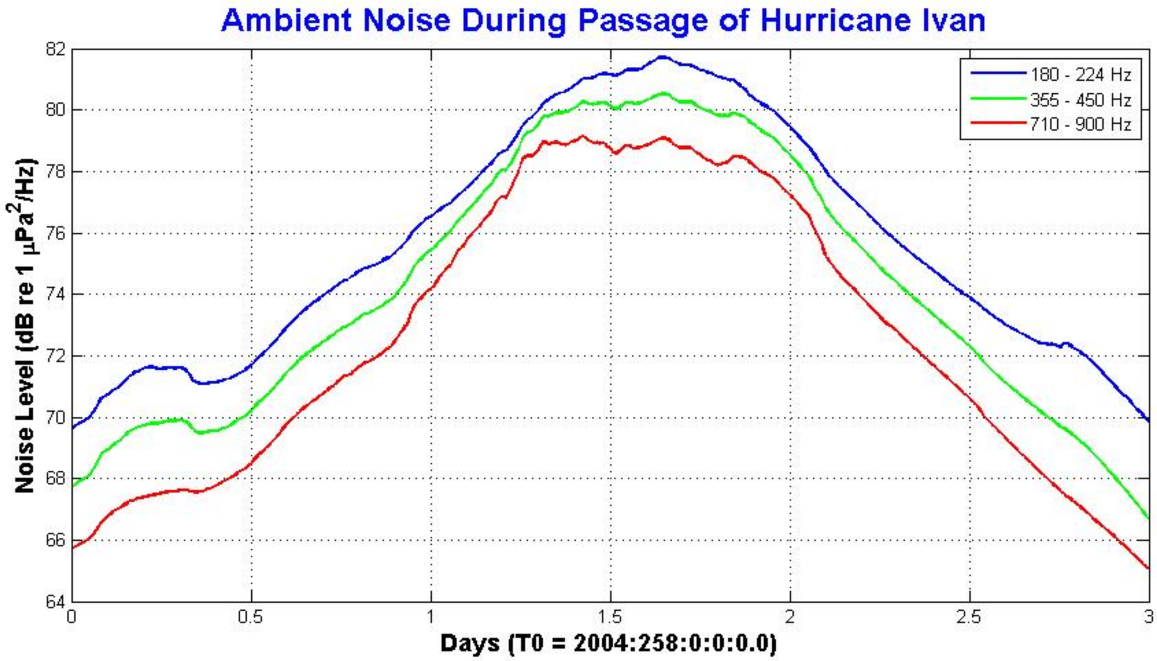

Fig. 10 Ambient noise during passage of Hurricane Ivan.

V. SUMMARY

The passage of one hurricane during August 2004 had negligible impact on the ambient noise statistics. Conversely, the passage of three hurricanes during September 2004 had a major impact on all of the statistical quantities measured. Of all the months studied, September 2004 had the highest average wind speed and the highest average significant wave height. The ambient noise levels at high frequencies (400-950 Hz) are elevated, as expected, and are highly correlated with the wind and wave height data. The ambient noise levels at low frequencies (25-100 Hz) are depressed, perhaps an indicator of less shipping activity during extreme wind conditions. The fewest number of peaks per day, as well as troughs per day, was observed from 200-950 Hz during September, yielding the smallest estimate of nearby ships per day. The average time between peaks, as well as troughs, was maximum from 200-950 Hz.

The variability of the data was high at high frequencies (400-950 Hz) during September, as indicated by the standard deviation and the spread of the data (the difference between the 10^{th} and the 90^{th} percentiles). The skewness was positive from 25-400 Hz, which corresponds with the frequency range for which the monthly mean noise was greater than the monthly median noise. Likewise, the skewness was negative from 630-950 Hz, which corresponds with the frequency range for which the monthly median noise was greater than the monthly mean noise. The kurtosis was high from 50-100 Hz, peaking at 100 Hz. The coherence time was maximum from 200-950 Hz, ranging from 10 hours at 200 Hz to 33 hours at 950 Hz.

The passage of Hurricane Ivan raised noise levels about 12 dB above background from 200-800 Hz. Noise levels in each of these bands increased at a rate of about 11 dB per day as Ivan approached and decreased by about 11 dB per day as Ivan departed.

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